White-box attack resistant cryptography

Hiding cryptographic keys against the powerful attacker

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CROCS
Centre for Research on
Cryptography and Security

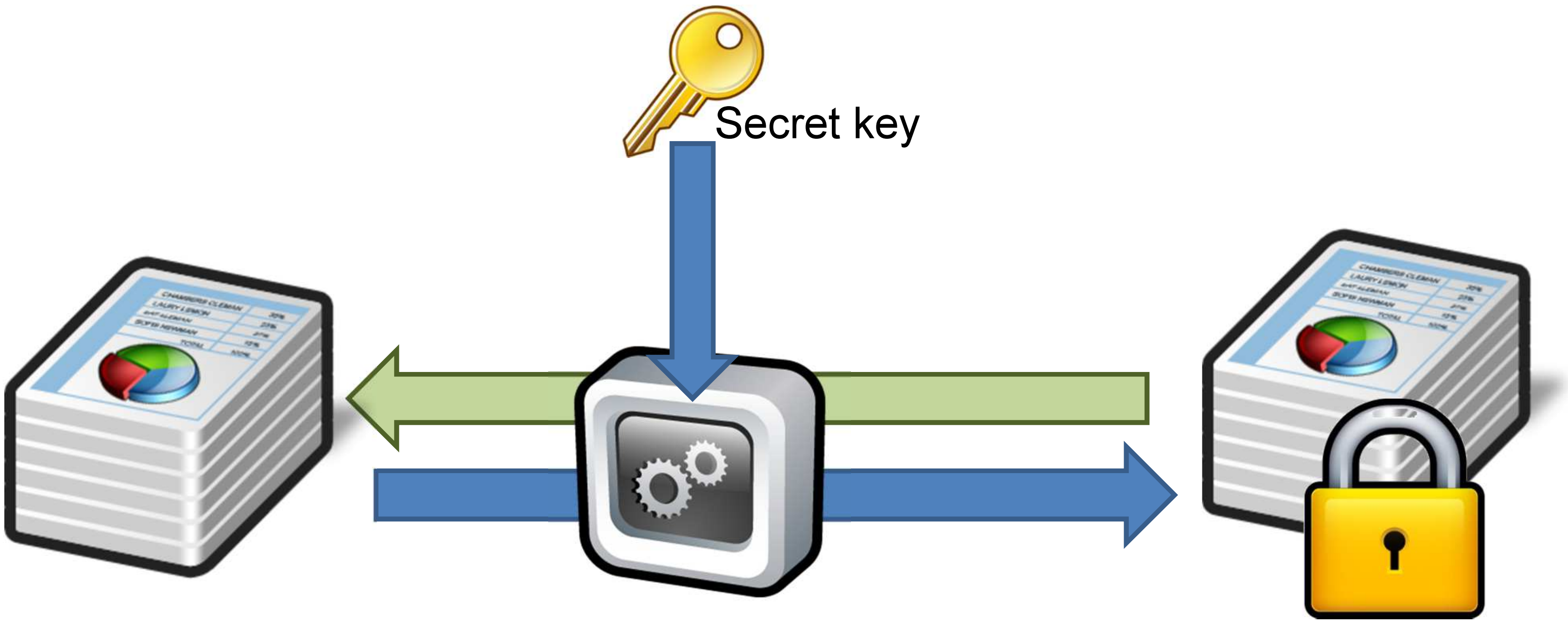
Outline

- Short intro to symmetric/asymmetric cryptography
- Classical implementations & related problems
- CEF&CED, practical problems
- Whitebox cryptography, whitebox-AES
- Available implementations & attacks
- Future work, related R&D at CROCS@FIMU

Protecting key material for cryptographic functions

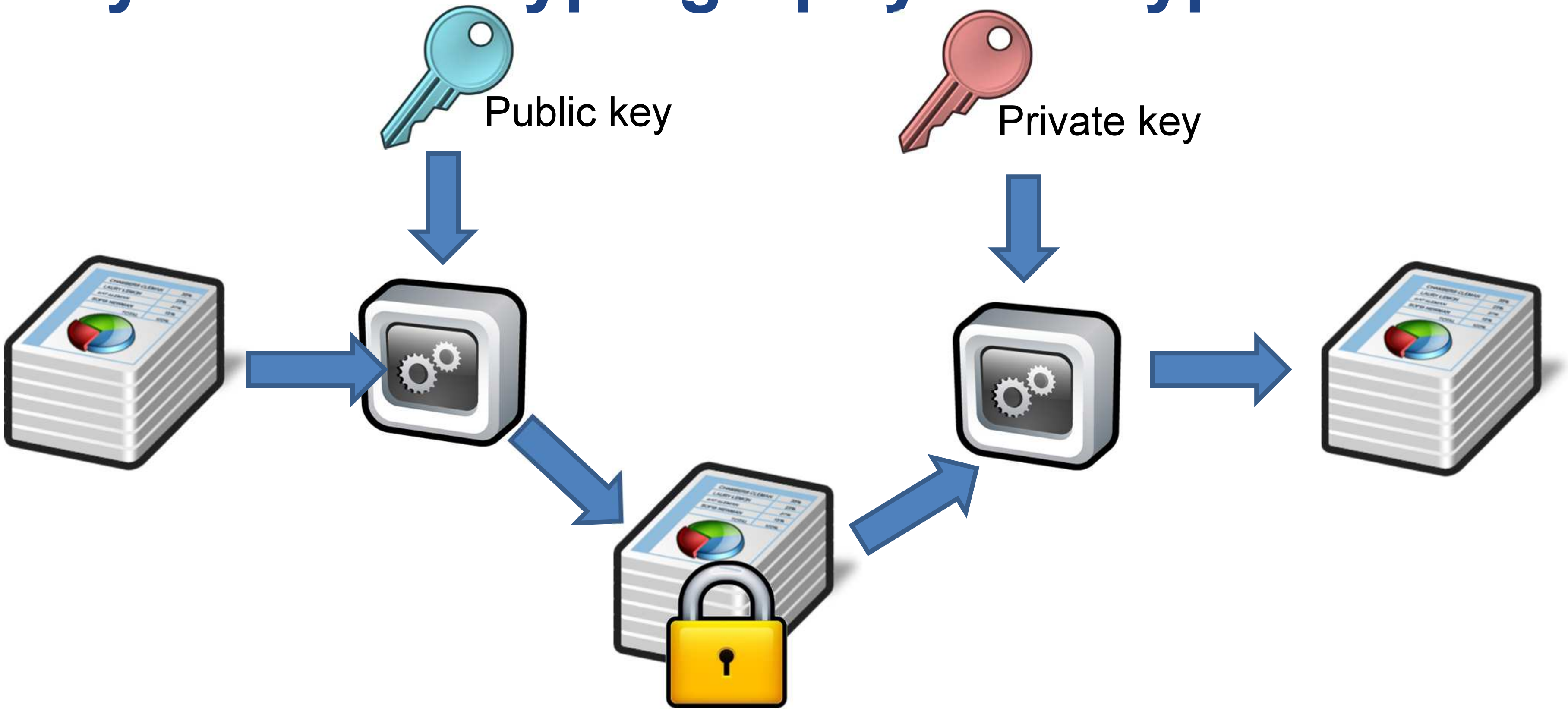
TROUBLES WITH KEYS

Cryptography with symmetric key



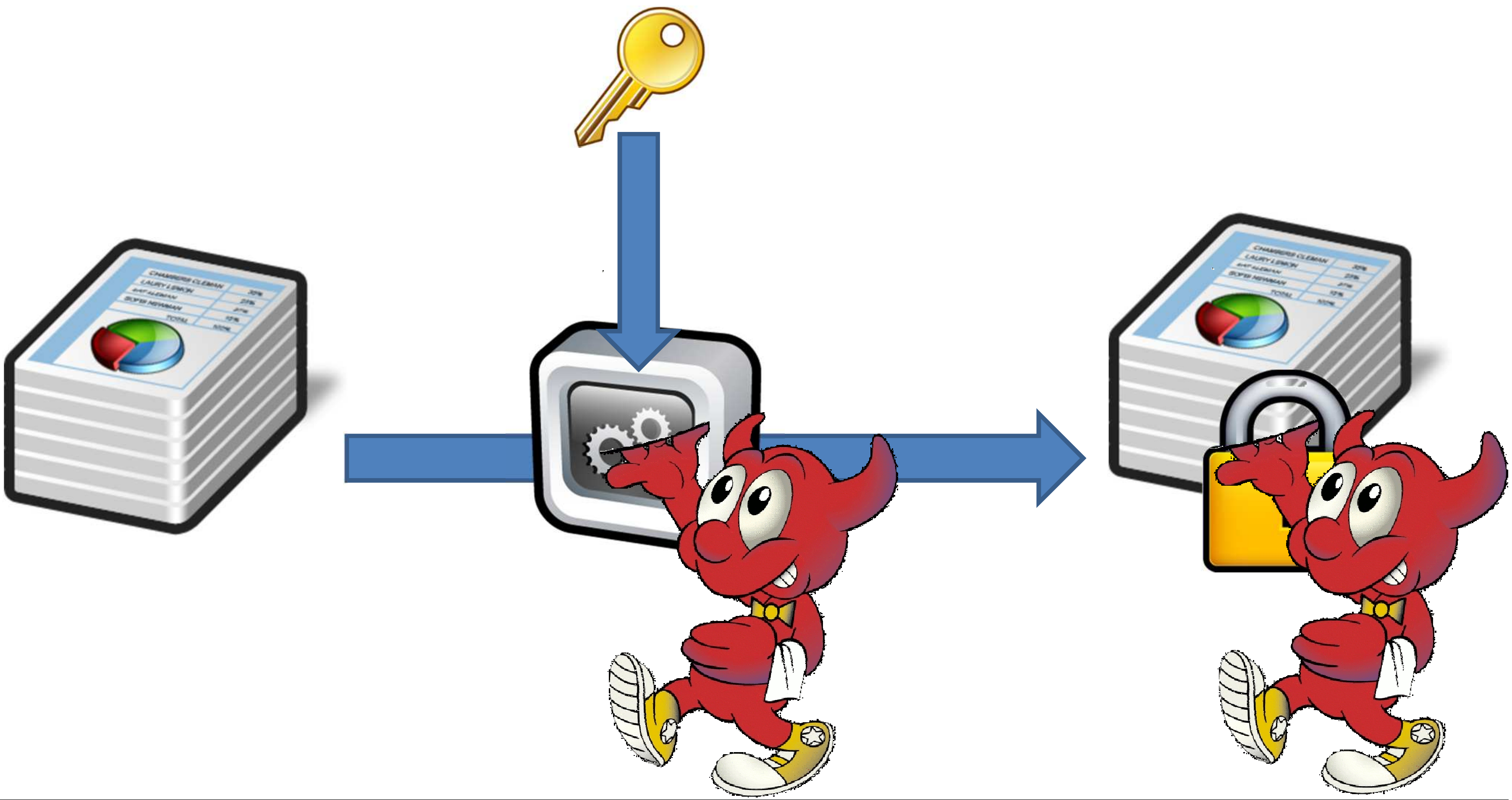
- Algorithms: DES, AES, Blowfish, IDEA, RC4...
- Key lengths: 16-32 bytes
- Usage: encryption, cryptographic checksum, auth.

Asymmetric cryptography - encryption



- Algorithms: RSA, Diffie-Hellman, ECC...
- Key lengths: 32 bytes (ECC-256) – 256 bytes (RSA-2048)
- Usage: encryption, digital signature, authentication

Standard vs. whitebox attacker model



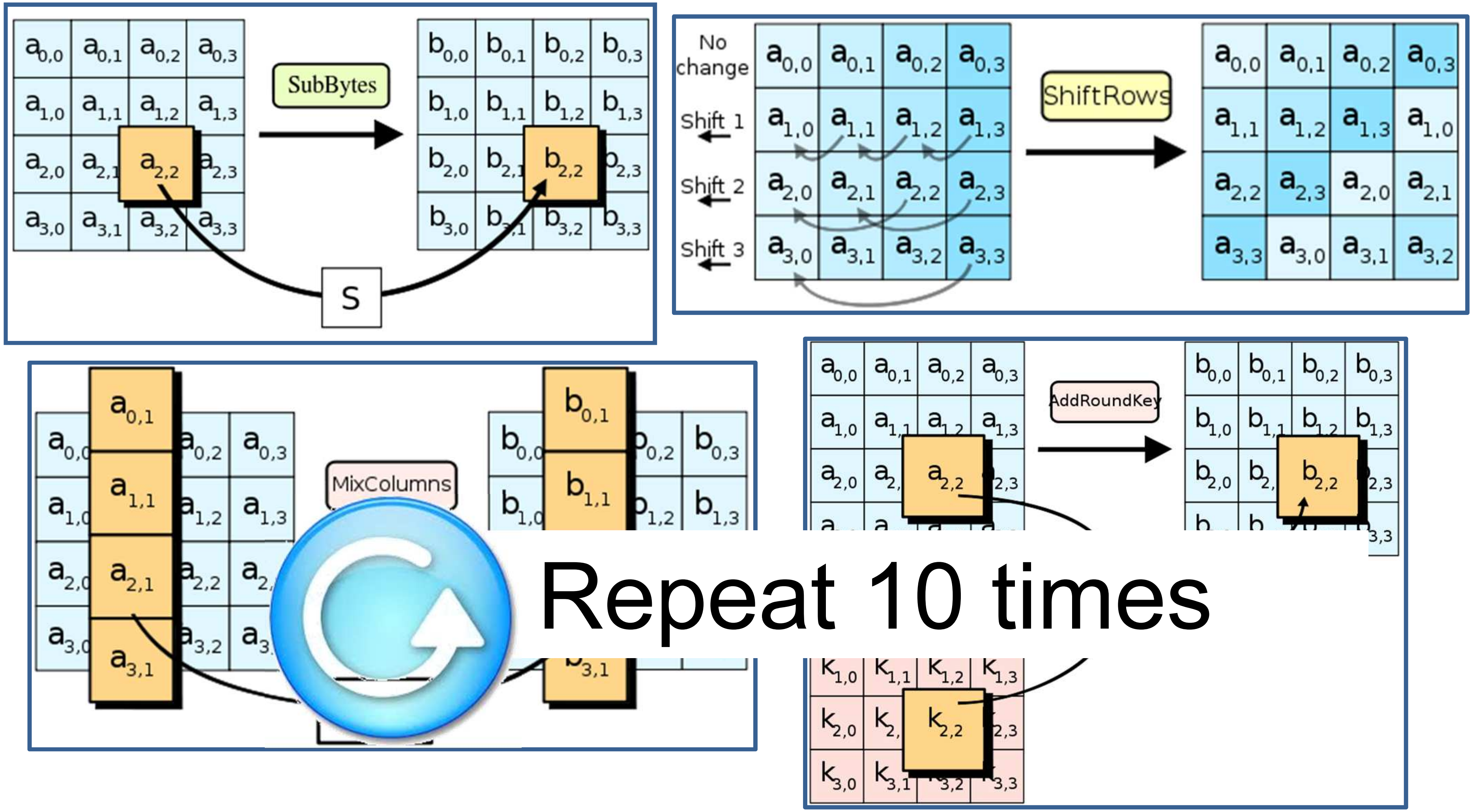
Standard AES API (PolarSSL)

```
/**
 * \brief          AES key schedule (encryption)
 *
 * \param ctx      AES context to be initialized
 * \param key      encryption key
 * \param keysize  must be 128, 192 or 256
 *
 * \return         0 if successful, or POLARSSL_ERR_AES_INVALID_KEY_LENGTH
 */
int aes_setkey_enc(aes_context *ctx, const unsigned char *key, unsigned int keysize);

/**
 * \brief          AES-ECB block encryption/decryption
 *
 * \param ctx      AES context
 * \param mode     AES_ENCRYPT or AES_DECRYPT
 * \param input    16-byte input block
 * \param output   16-byte output block
 *
 * \return         0 if successful
 */
int aes_crypt_ecb( aes_context *ctx,
                   int mode,
                   const unsigned char input[16],
                   unsigned char output[16] );
```

Pictures taken from http://en.wikipedia.org/wiki/Advanced_Encryption_Standard

Advanced Encryption Algorithm



Standard AES - usage

```
void simpleAES() {
    unsigned char key[32];
    unsigned char buf[16];
    aes_context ctx;

    memset( buf, 1, sizeof(buf));
    memset( &ctx, 0, sizeof(ctx));

    // Set the key
    sprintf((char*)key, "%s", "SecurePassword:nbu123");
    aes_setkey_enc( &ctx, key, 128);

    printf("Input:  ");
    for (int i = 0; i < AES_BLOCK_SIZE; i++) printf("%2x", buf[i]);
    printf("\n");

    // Encrypt one block
    aes_crypt_ecb( &ctx, AES_ENCRYPT, buf, buf );
    printf("Output:  ");
    for (int i = 0; i < AES_BLOCK_SIZE; i++) printf("%x", buf[i]);
}
```

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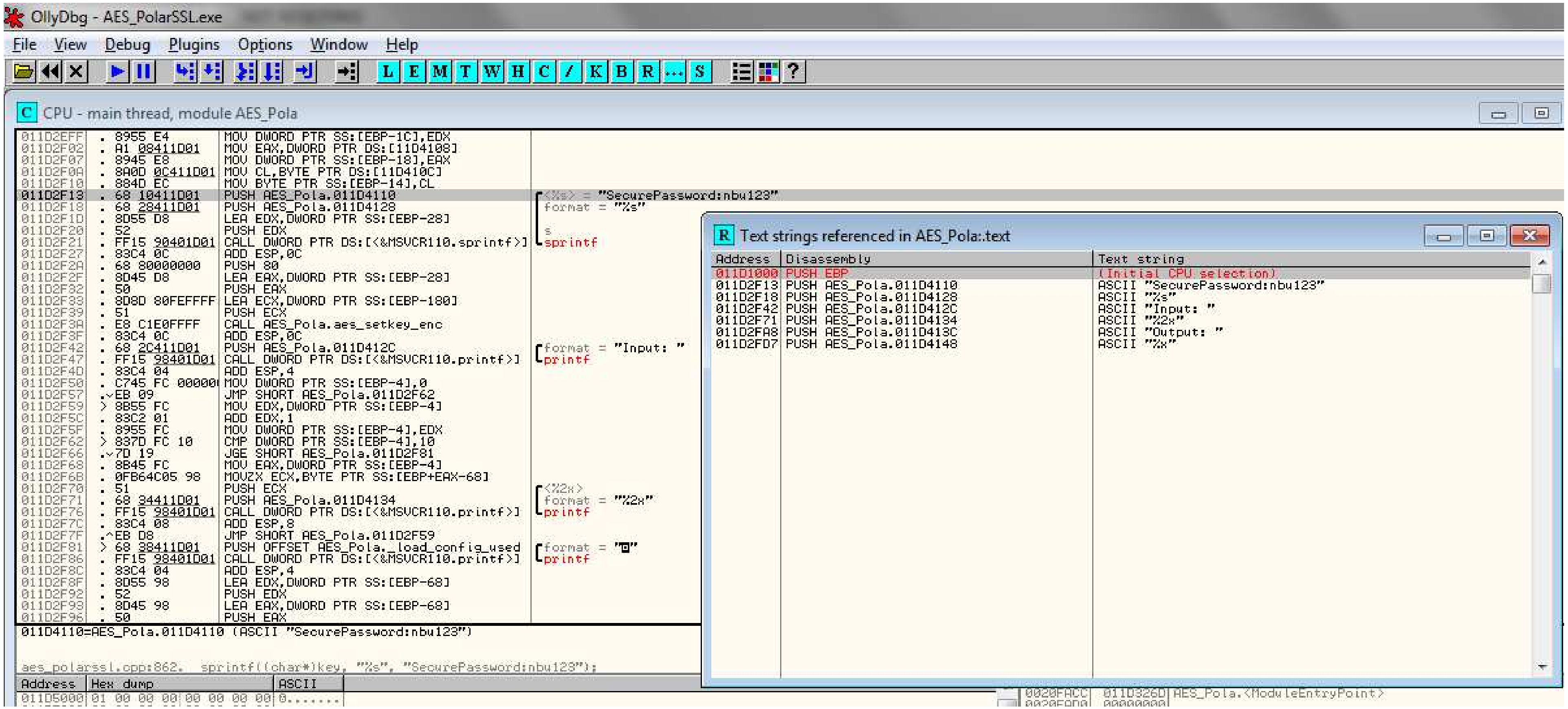
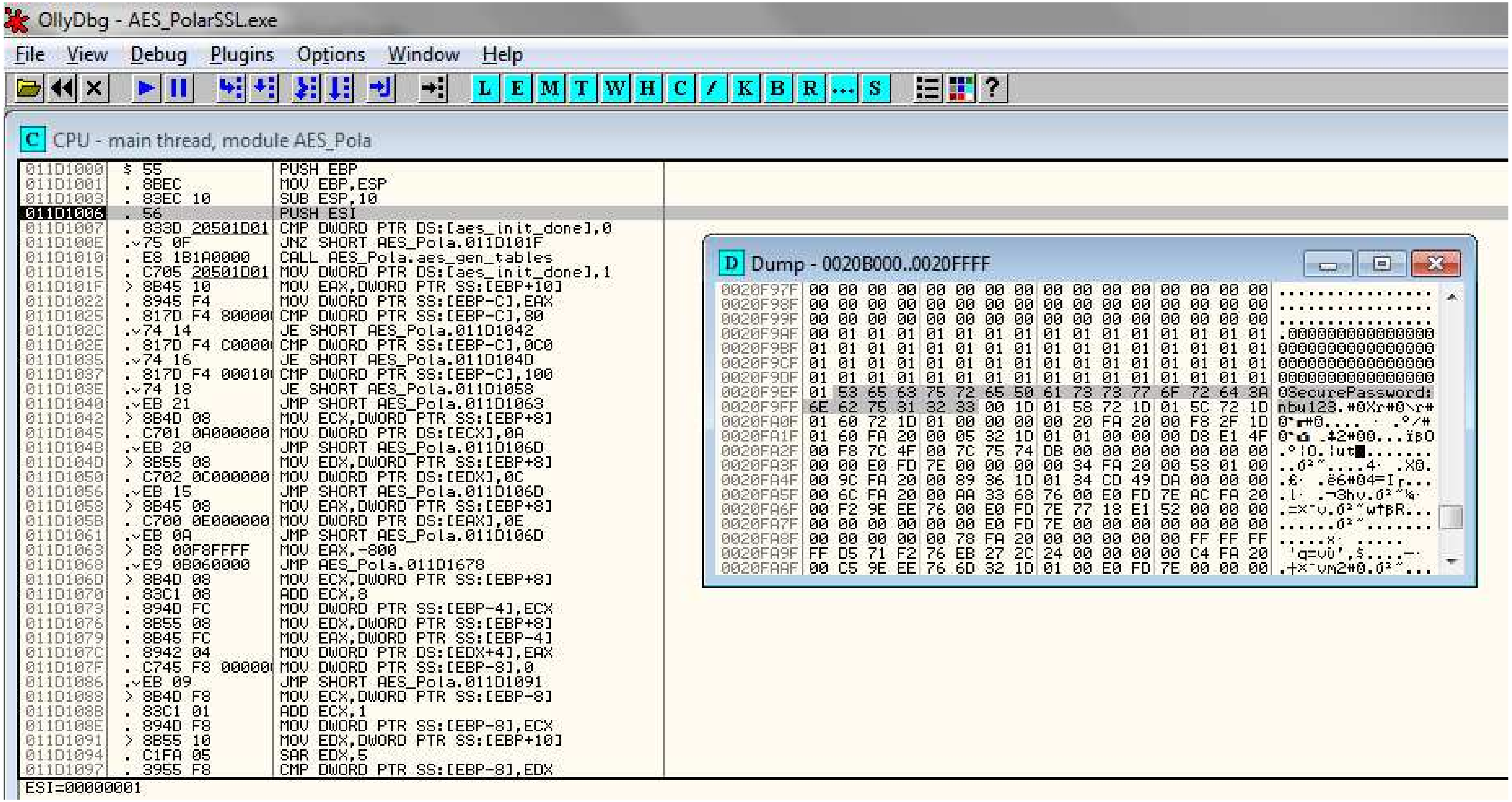
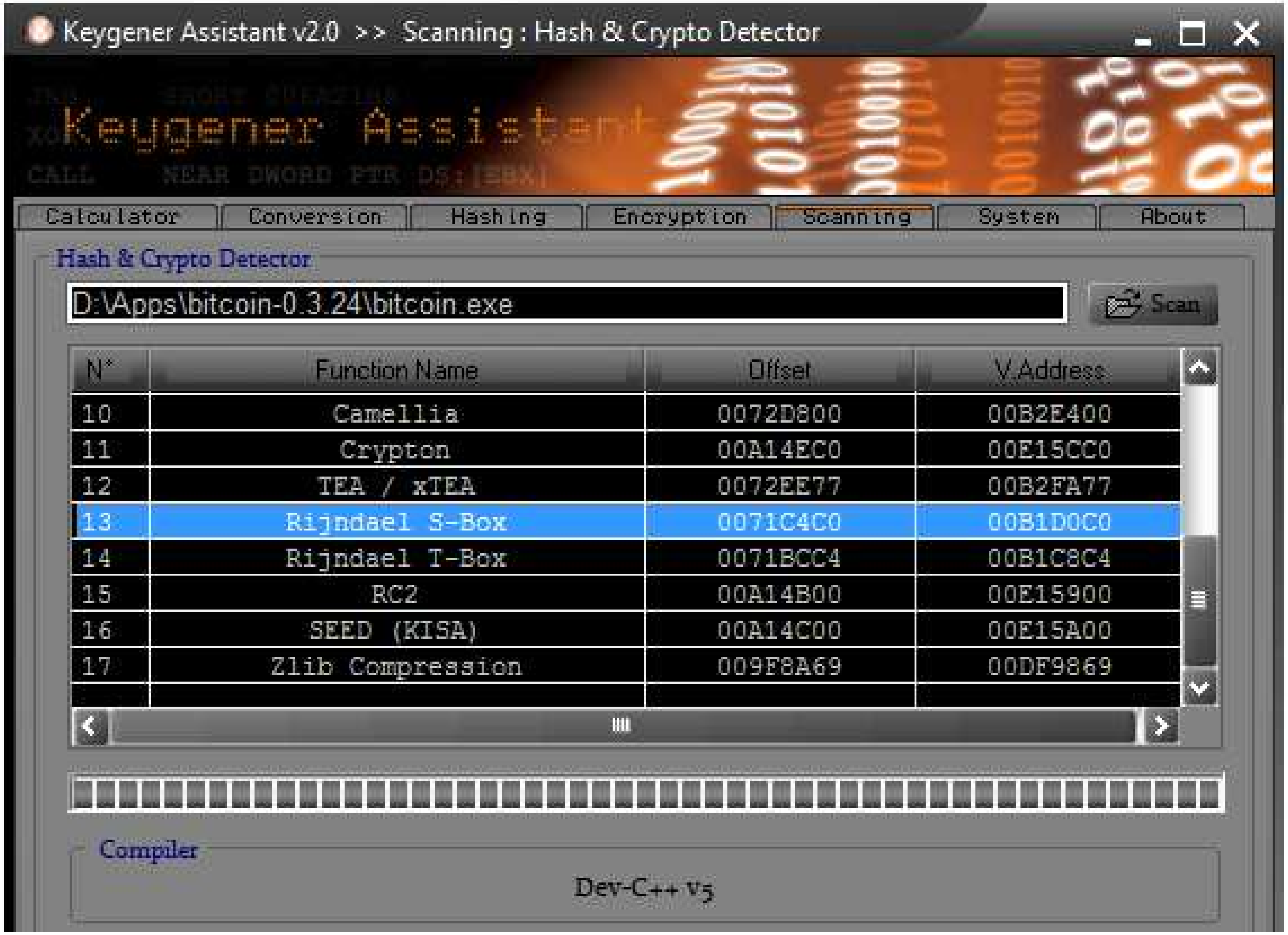
OllyDbg – key value is static string



OllyDbg – key is visible in memory



What if AES usage is somehow hidden?



Whitebox attacker model

- The attacker is able to:
  - inspect and disassemble binary (static strings, code...)
  - observe/modify all executed instructions (OllyDbg...)
  - observe/modify used memory (OllyDbg, memory dump...)
- How to still protect value of cryptographic key?
- Who might be whitebox attacker?
  - Mathematician (for fun)
  - Security researcher / Malware analyst (for work)
  - DRM cracker (for fun&profit)
  - ...

Classical obfuscation and its limits

- Time-limited protection
- Obfuscation is mostly based on obscurity
  - add bogus jumps
  - reorder related memory blocks
  - transform code into equivalent one, but less readable
  - pack binary into randomized virtual machine
  - ...
- Barak's (im)possibility result (2001)
  - family of functions that will always leak some information
  - but practical implementation may exists for others

Computation with Encrypted Data and Encrypted Function

CEF&CED

Scenario

- We'd like to compute function F over data D
  - secret algorithm F or sensitive data D (or both)
- Solution with trusted environment
  - my trusted PC, trusted server, trusted cloud…
- Problem: can be cloud or client really trusted?
  - server hack, DRM, malware...
- Attacker model
  - controls execution environment (debugging)
  - sees all instructions and data executed

CEF

- Computation with Encrypted Function (CEF)
  - A provides function F in form of P(F)
  - P can be executed on B’s machine with B’s data D as P(D)
  - B will not learn function F during computation

CED

- Computation with Encrypted Data (CED)
  - B provides encrypted data D as E(D) to A
  - A is able to compute its F as F(E(D)) to produce E(F(D))
  - A will not learn D

CED via homomorphism

1. Convert your function into circuit with additions (`xor`) and multiplications (`and`) only
2. Compute addition and/or multiplication “securely”
   - an attacker can compute E(D1+D2) = E(D1)+E(D2)
   - but will learn neither D1 nor D2
3. Execute whole circuit over encrypted data

- Partial homomorphic scheme
  - either addition or multiplication is possible, but not both
- Fully homomorphic scheme
  - both addition and multiplication (unlimited)

Partial homomorphic schemes

- Example with RSA (*multiplication*)
  - $E(d_1).E(d_2) = d_1^e \,.\, d_2^e \bmod m = (d_1 d_2)^e \bmod m = E(d_1 d_2)$
- Example Goldwasser-Micali (*addition*)
  - $E(d_1).E(d_2) = x^{d1} r_1^2 \cdot X^{d2} r_2^2 = x^{d1+d2} (r_1 r_2)^2 = E(d_1 \oplus d_2)$
- Limited to polynomial and rational functions
- Limited to only one type of operation (*mult* or *add*)
  - or one type and very limited number of other type
- Slow – based on modular mult or exponentiation
  - every operation equivalent to whole RSA operation

Fully homomorphic scheme (FHE)

- Holy grail - idea proposed in 1978 (Rivest et al.)
  - both addition and multiplication securely
- But no scheme until 2009 (Gentry)!
  - based on lattices over integers
  - noisy FHE usable only to few operations
  - combined with repair operation

Fully homomorphic scheme - usages

- Outsourced cloud computing and storage (FHE search)
  - Private Database Queries
  - using Somewhat Homomorphic Encryption http://researcher.ibm.com/researcher/files/us-shaih/privateQueries.pdf
  - protection of the query content
- Secure voting protocols (yes/no + sum)
- Protection of proprietary info - MRI machines
  - very expensive algorithm analyzing MR data, HW protected
  - central processing restricted due to processing of private patient data
- Read more about current state of FHE
  - http://www.americanscientist.org/issues/id.15906,y.2012,no.5,content.true,page.2,css.print/issue.aspx

Fully homomorphic scheme - practicality

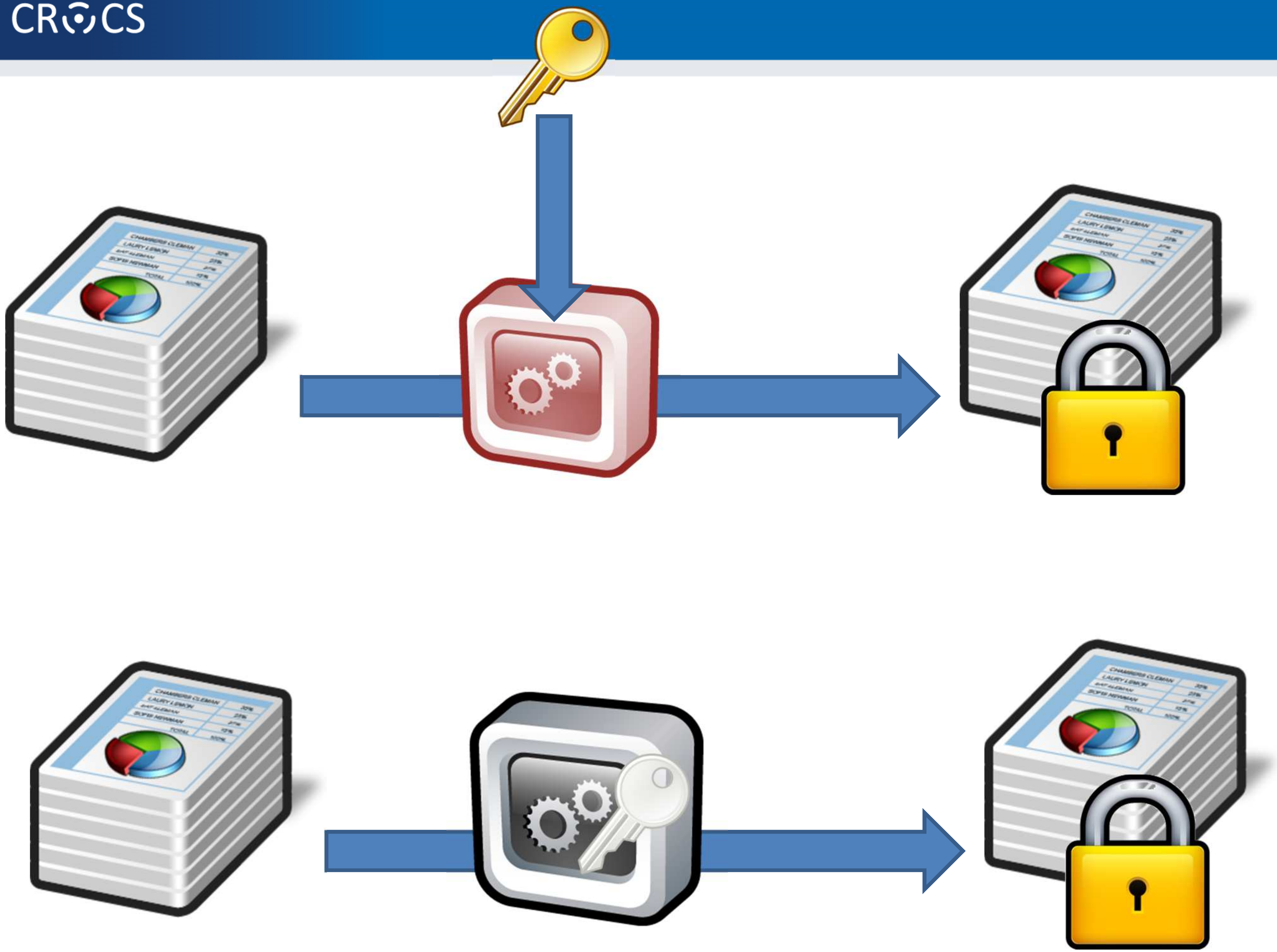
- Not very practical (yet ☺) (Gentry, 2009)
  - 2.7GB key & 2h computation for every repair operation
  - repair needed every ~10 multiplication
- FHE-AES implementation (Gentry, 2012)
  - standard PC ⇒ 37 minutes/block (but 256GB RAM)

Protection of cryptographic primitives

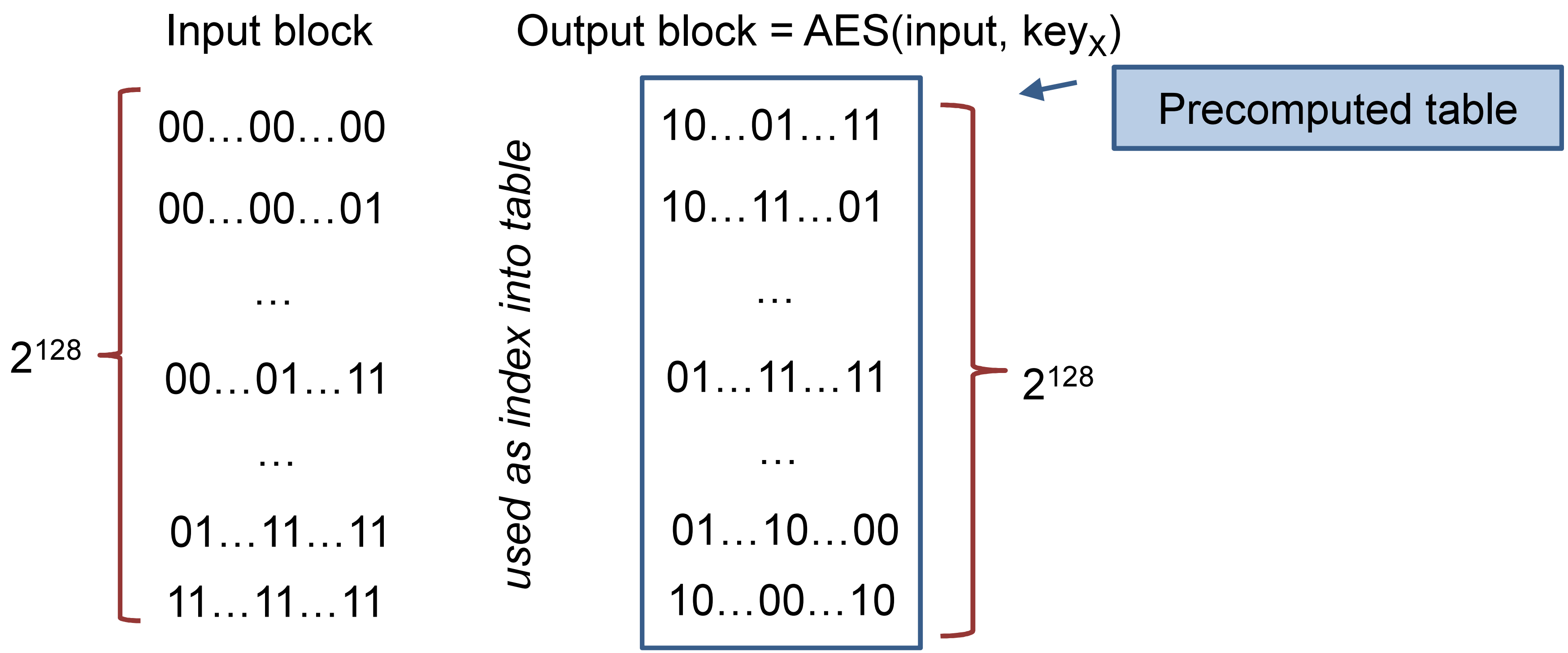
WHITEBOX RESISTANT CRYPTO

White-box attack resistant cryptography

- Problem limited from every cipher to symmetric cryptography cipher only
  - protects used cryptographic key (and data)
- Special implementation fully compatible with standard AES/DES… 2002 (Chow et al.)
  - series of lookups into pre-computed tables
- Implementation of AES which takes only data
  - key is already embedded inside
  - hard for an attacker to extract embedded key



Impractical solution



- Secure, but 2^{128} x 16B memory storage

WBACR AES – some techniques

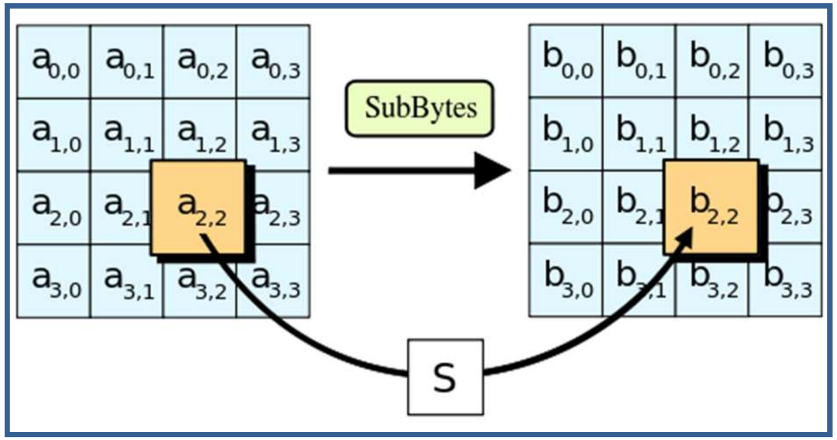
- Pre-compute table for all possible inputs
  - practical for one 16bits or two 8bits arguments table with up to 2^{16} rows (~64KB)
  - **`AddRoundKey: data ⊕ key`**
    - 8bit argument data, key fixed

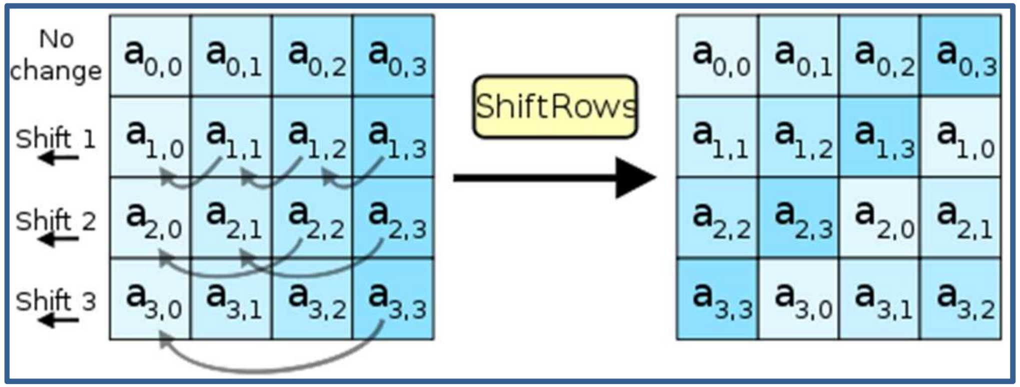
$$\left.\begin{array}{|c|}\hline 10\ldots01\ldots11 \\ 10\ldots11\ldots01 \\ \ldots \\ 01\ldots11\ldots11 \\ \ldots \\ 01\ldots10\ldots00 \\ 10\ldots00\ldots10 \\ \hline\end{array}\right\} 2^8$$

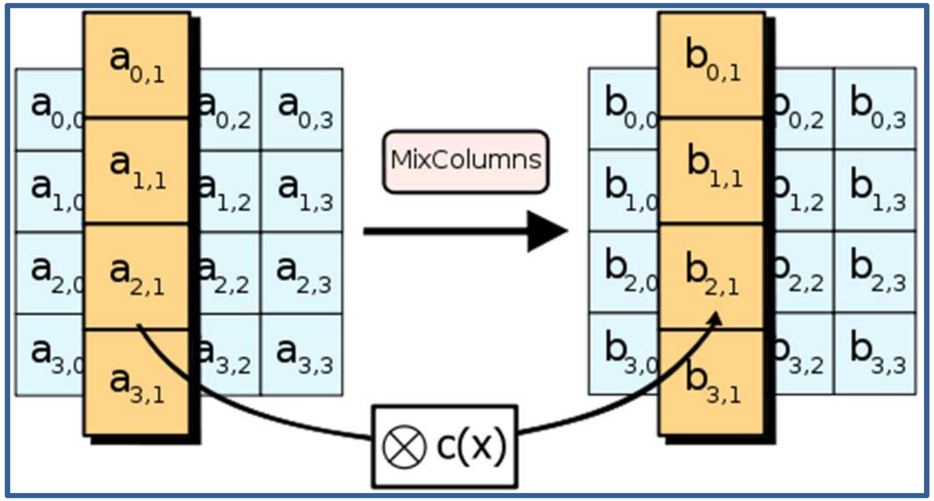
- Pack several operations together
  - **`AddRoundKey+SubBytes: T[i] = S[i ⊕ key];`**
- Protect intermediate values by random bijections
  - removed automatically by next lookup
  - $\mathtt{X = F^{-1}(F(X))}$
  - $\mathtt{T[i] = S[F^{-1}(i) \oplus key];}$

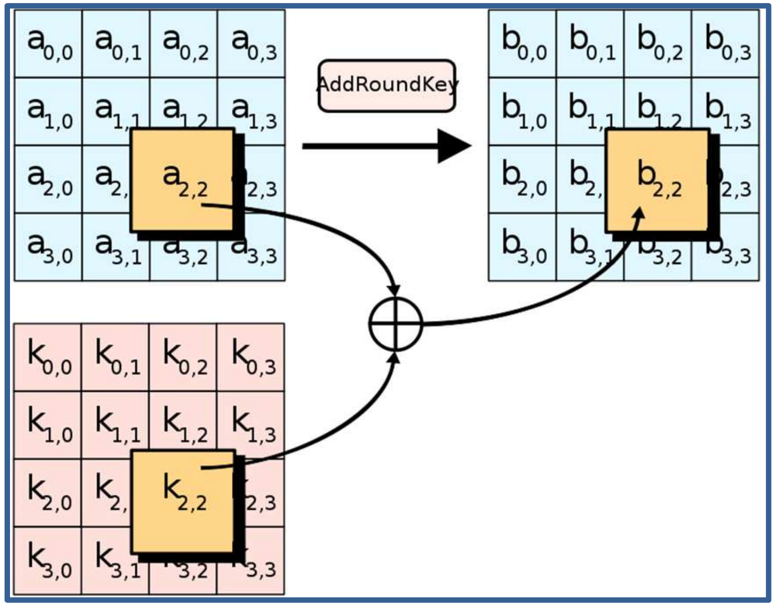
Pictures taken from http://en.wikipedia.org/wiki/Advanced_Encryption_Standard

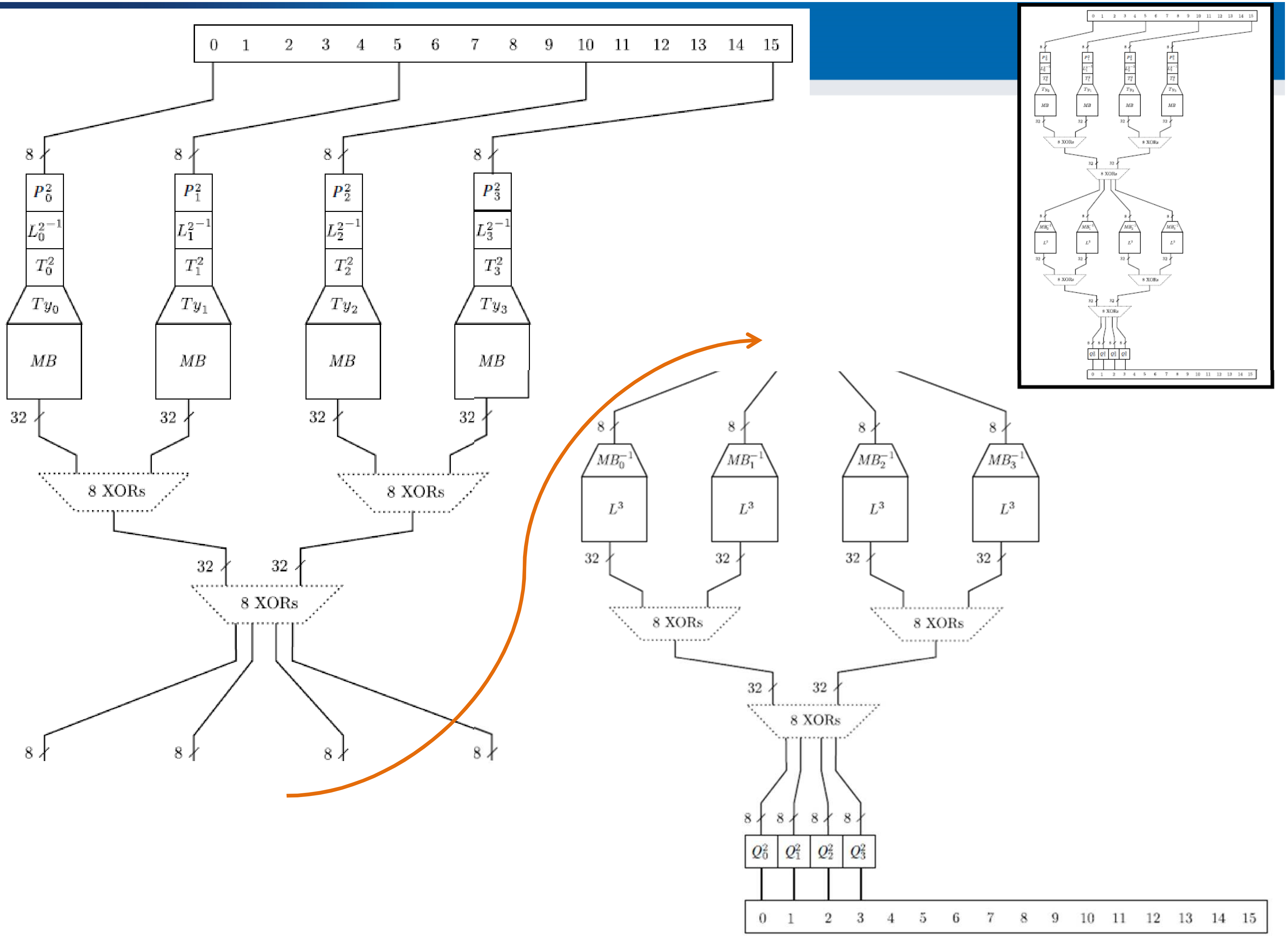
AES – short remainder (used ops)





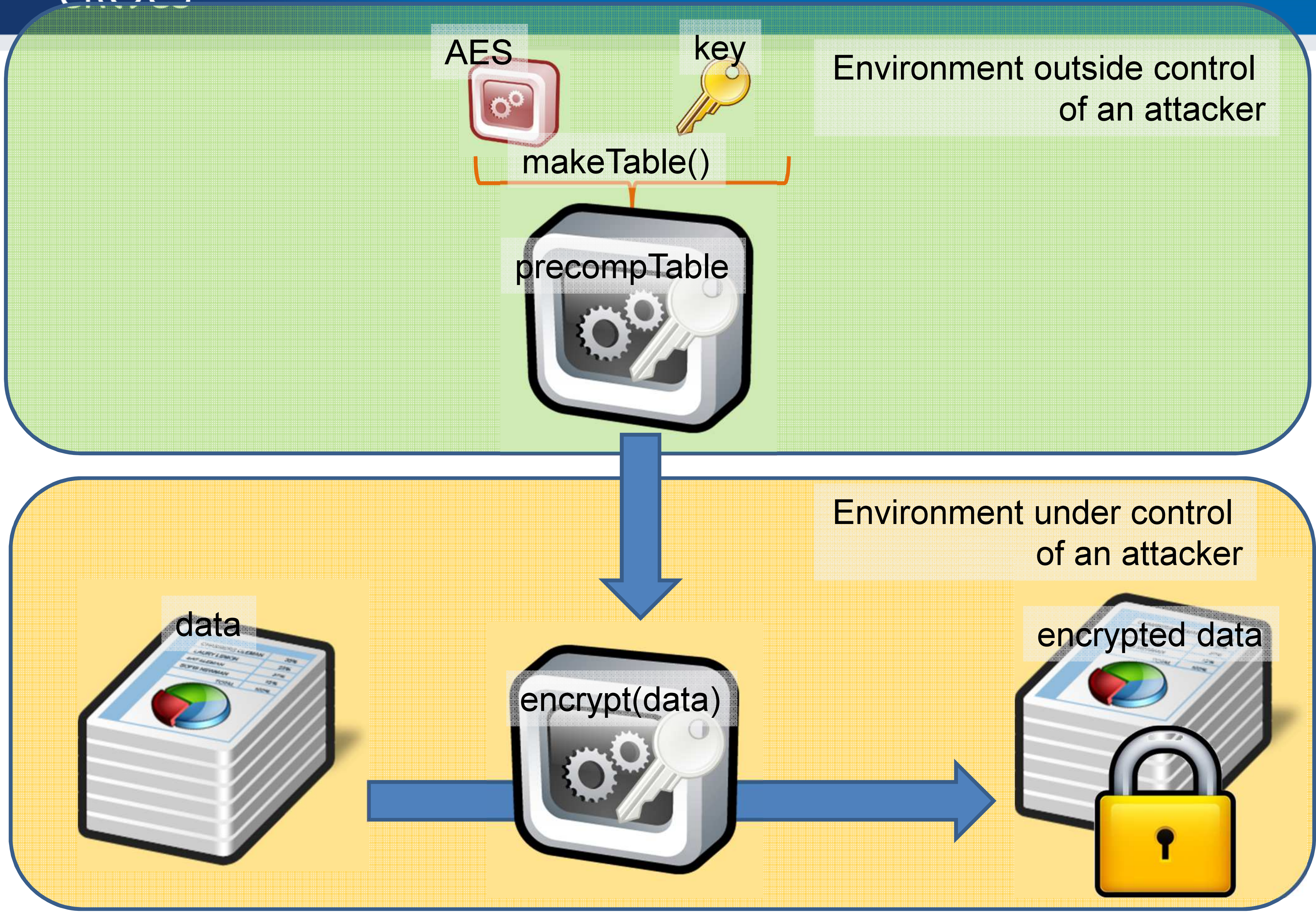





0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
8
P_0^2 P_1^2 P_2^2 P_3^2
$L_0^{2^{-1}}$ $L_1^{2^{-1}}$ $L_2^{2^{-1}}$ $L_3^{2^{-1}}$
T_0^2 T_1^2 T_2^2 T_3^2
Ty_0 Ty_1 Ty_2 Ty_3
MB
32
8 XORs
MB_0^{-1} MB_1^{-1} MB_2^{-1} MB_3^{-1}
L^3
Q_0^2 Q_1^2 Q_2^2 Q_3^2

Whitebox cryptography lifecycle

- [Secure environment]
  1. Generate required key (random, database...)
  2. Generate WAES tables (in secure environment)
- [Potential insecure environment]
  3. Compile WAES tables into target application
- [Insecure environment (User PC)]
  4. Run application and use WAES as usual (with fixed key)


AES
key
Environment outside control
of an attacker
makeTable()
precompTable
Environment under control
of an attacker
data
encrypted data
encrypt(data)

Resulting implementation

- More difficult to detect that crypto was used
  - no fixed constants in the code
  - precomputed tables change with every generation
  - even two tables for same key are different
  - (but can still be found)
- Resistant even when precomputed tables are found
  - when debugged, only table lookups are seen
  - key value is never manipulated in plaintext
  - transformation techniques should provide protection to key embedded inside tables

WBACR AES - pros

- Practically usable
  - implementation size ~800KB (tables)
  - speed ~MBs/sec (~6.5MB/s vs. 220MB/s)
- Hard to extract embedded key
  - Complexity semi-formally guaranteed
  - (if the scheme is secure)
- One can simulate asymmetric cryptography!
  - implementation contains only encryption part of AES
  - until attacker extracts key, decryption is not possible

WBACR AES - cons

- Implementation can be used as oracle (black box)
  - attacker can supply inputs and obtain outputs
  - even if she cannot extract the key
  - (can be partially solved by I/O encodings)
- Problem of secure input/output
  - protected is only AES, not code around
- Key is fixed and cannot be easily changed
- Successful cryptanalysis for several schemes
  - several former schemes broken
  - new techniques proposed

Can whitebox transform replace secure hardware (e.g., smart card)?

- Only to limited extent
- Limitation of arguments size
- Operation atomicity
  - one cannot execute only half of card’s operations
- No secure memory storage
  - no secure update of state (counter)
- Both can be used as black-box
  - smart card can use PIN to limit usage
- But still some reasonable usages remain

List of proposals and attacks

- (2002) First WB AES implementation by Chow et. al. [Chow02]
  - IO bijections, linear mixing bijections, external coding
  - broken by BGE cryptanalysis [Bill04]
    - algebraic attack, recovering symmetric key by modelling round function by system of algebraic equations
- (2006) White Box Cryptography: A New Attempt [Bri06]
  - attempt to randomize whitebox primitives, perturbation & random equations added, S-boxes are enc. keys. 4 AES ciphers, major voting for result
  - broken by Mulder et. al. [Mul10]
    - removes perturbations and random equations, attacking on final round removing perturbations, structural decomposition. 2^{17} steps
- (2009) A Secure Implementation of White-box AES [Xia09]
  - broken by Mulder et. al. [Mul12]
    - linear equivalence algorithm used (backward AES-128 compatibility => linear protection has to be inverted in next round), 2^{32} steps
- (2011) Protecting white-box AES with dual ciphers [Kar11]
  - broken by our work [Kli13]
    - protection shown to be ineffective

More resources

- Overviews, links
  - http://whiteboxcrypto.com/research.php
  - https://minotaur.fi.muni.cz:8443/~xsvenda/docuwiki/doku.php?id=public:mobilecrypto
- Crackme challenges
  - http://www.phrack.org/issues.html?issue=68&id=8
- Whitebox crypto in DRM
  - http://whiteboxcrypto.com/files/2012_MISC_DRM.pdf

Whitebox transform IS used in the wild

- Proprietary DRM systems
  - details are usually not published
  - AES-based functions, keyed hash functions, RSA, ECC...
  - interconnection with surrounding code
- Chow at al. (2002) proposal made at Cloakware
  - firmware protection solution
- Apple's FairPlay & Brahms attack
  - http://whiteboxcrypto.com/files/2012_MISC_DRM.pdf
- TrojanSpy:Win32/WhiteBox? ☺
- ...

Available practical implementations

DEMO

Demo – WAES

- WAES tables generator
  - configuration options
  - *.h files with pre-computed tables
- WAES cipher implementation
  - compile-in tables
  - tables as memory blob

```
# Encryption and decryption key values. Used during "/g:" option .
[KEY_VALUE]
# Key value which will be used for encryption part of WBACR AES tables.
# CAN be different from decryptKey
encryptKey=8a b1 21 d3 13 d1 5e 31 29 84 4c 66 50 14 6e 95
# Key value which will be used for decryption part of WBACR AES tables.
decryptKey=00 01 02 03 05 06 07 08 0A 0B 0C 0D 0F 10 11 12
# Additional entropy used for WBACR DES tables pre-computation
entropy=4d 28 a7 cd f9 c6 64 bc 94 c4 0e 77 79 7a 41 dc d8 19 9a 4b 0e 1c
```

```
#ifndef AESINVFIRSTTABLE_AUTH_H
#define AESINVFIRSTTABLE_AUTH_H

BYTE            invFirstRoundTable_auth[4][4][256] = {
{
{0x23, 0xee, 0x4c, 0x94, 0x4e, 0x32, 0x95, 0x3d, 0xa6, 0x
0xff, 0x34, 0x8e, 0x39, 0xcb, 0x82, 0x43, 0x87, 0x9b, 0xe
0xf, 0xc1, 0xaf, 0x1e, 0x6b, 0x8f, 0xbd, 0x2, 0xca, 0x8a,
0xc7, 0xb1, 0x12, 0xa8, 0x5f, 0x33, 0x10, 0x31, 0x88, 0xe
0xd6, 0xe1, 0x69, 0x4, 0x7d, 0x7e, 0x14, 0x26, 0xba, 0xc,
0x35, 0xe2, 0xf9, 0x74, 0x6e, 0x22, 0x37, 0x85, 0xe7, 0xc
0x24, 0x76, 0x5b, 0xa1, 0x25, 0x66, 0xa2, 0xb2, 0x28, 0xc
0x79, 0x9a, 0xdb, 0x3e, 0xf4, 0x4b, 0xc0, 0x20, 0xc6, 0x5
0xf5, 0xc8, 0xeb, 0x3b, 0x61, 0x4d, 0xbb, 0xb0, 0xae, 0x9
0xb9, 0x5e, 0x15, 0x48, 0x84, 0x50, 0x46, 0xda, 0xfd, 0x9
```

WAES performance

- Intel Core i5 M560@2.67GHz

Test	Result	Additional info.	OpenSSL result
generate WB AES	8.48 s avg.	100 samples	
throughput, 1 MB random	867.8 KB/s	1.18 s	57283 KB/s
throughput, 10 MB random	1022.977 KB/s	10.01 s	54179 KB/s
throughput, 100 MB random	1028.319 KB/s	99.58 s	74744 KB/s
throughput, 1024 MB random	1124.792 KB/s	932.24 s	63723 KB/s
throughput, 1 MB null	975 KB/s	1.05 s	93091 KB/s
throughput, 10 MB null	969.970 KB/s	10.56 s	68821 KB/s
throughput, 100 MB null	1058.507 KB/s	96.74 s	56356 KB/s
throughput, 1024 MB null	1050.593 KB/s	998.08 s	57283 KB/s

Table 4.2: Results of the benchmark for whitebox AES generator

BGE attack in progress

```
   recoverQj; q = 0x88; gamma=0x01;
   recoverQj self-test; r=5; col=3; (y0, y3); P[0].deltaInv=0x03; alfa_{3,0}=0x03
   recoverQj self-test; r=5; col=3; (y0, y3); P[1].deltaInv=0x01; alfa_{3,1}=0x01
   recoverQj self-test; r=5; col=3; (y0, y3); P[2].deltaInv=0x01; alfa_{3,2}=0x01
   recoverQj self-test; r=5; col=3; (y0, y3); P[3].deltaInv=0x02; alfa_{3,3}=0x02
   recoverQj; q = 0x3c; gamma=0x01;

Going to reconstruct encryption key from extracted round keys...
* Round keys extracted from the process, r=3
 0x3d  0x47  0x1e  0x6d  0x80  0x16  0x23  0x7a  0x47  0xfe  0x7e  0x88  0x7d  0x3e  0x44  0x3b

* Round keys extracted from the process, r=4
 0xef  0xa8  0xb6  0xdb  0x44  0x52  0x71  0x0b  0xa5  0x5b  0x25  0xad  0x41  0x7f  0x3b  0x00

* Round keys extracted from the process, r=5
 0xd4  0x7c  0xca  0x11  0xd1  0x83  0xf2  0xf9  0xc6  0x9d  0xb8  0x15  0xf8  0x87  0xbc  0xbc

Recovering cipher key from round keys...
We have correct Rcon! rconIdx=3
RC=2; previousKey:
 0xf2  0x7a  0x59  0x73
 0xc2  0x96  0x35  0x59
 0x95  0xb9  0x80  0xf6
 0xf2  0x43  0x7a  0x7f

RC=1; previousKey:
 0xa0  0x88  0x23  0x2a
 0xfa  0x54  0xa3  0x6c
 0xfe  0x2c  0x39  0x76
 0x17  0xb1  0x39  0x05

RC=0; previousKey:
 0x2b  0x28  0xab  0x09
 0x7e  0xae  0xf7  0xcf
 0x15  0xd2  0x15  0x4f
 0x16  0xa6  0x88  0x3c

Final result:
 0x2b  0x7e  0x15  0x16  0x28  0xae  0xd2  0xa6  0xab  0xf7  0x15  0x88  0x09  0xcf  0x4f  0x3c

Benchmark finished! Total time = 3a s; on average = 58 s; clocktime=57.66 s;
```

What’s in our pipeline?

FUTURE WORK

Webpage with implemented proposals

- Obvious next step ☺
- Relevant academic papers didn't come with implementation ☹
  - true both for proposals and attacks
- Our work provided 2 implementations & 2 attacks
  - we will do remaining soon
- Relevant links
- CrackMe challenges
- http://www.fi.muni.cz/~xsvenda/whiteboxcrypto/

Modifications to W-AES

- Break backward AES compatibility $\rightarrow$ new cipher
  - but same scheme, strong primitives, key dependency

1. Hash-chain generated round keys
   - noninvertible
2. Key-dependent confusion / S-boxes
   - high variability (13 bytes dependence)
3. Key-dependent diffusion
   - 32x32 -> 128x128 matrix
4. Incorporating of algebraic incompatible operations
   - like in IDEA cipher

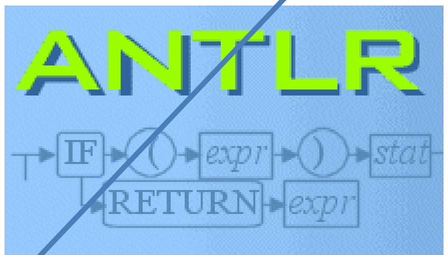
Automatic white-box code transformation

- Parse existing source code
- Identify “transformable” operations
  - suitable size of operands
  - no side effects
  - …
- Transform operations into white-box representation
  - or move to smart card
- Update existing code accordingly

```
for (i = start; i < end; i += 2) {
    int16_t  cbits = 0;
    uint16_t xbits = 0;
    unsigned int xlen = h->xlen;
    unsigned int ext = 0;
    unsigned int x1 = gi->l3_enc[i];
    unsigned int x2 = gi->l3_enc[i + 1];

    assert(gi->l3_enc[i] >= 0);
    assert(gi->l3_enc[i+1] >= 0);

    if (x1 != 0u) {
       if (gi->xr[i] < 0.0f)
          ext++;
       cbits--;
    }

    if (tableindex > 15u) {
       /* use ESC-words */
       if (x1 >= 15u) {
          uint16_t const linbits_x1 = x1 - 15u;
          assert(linbits_x1 <= h->linmax);
          ext |= linbits_x1 << 1u;
          xbits = linbits;
          x1 = 15u;
       }

       if (x2 >= 15u) {
          uint16_t const linbits_x2 = x2 - 15u;
          assert(linbits_x2 <= h->linmax);
          ext <<= linbits;
          ext |= linbits_x2;
          xbits += linbits;
          x2 = 15u;
       }
       xlen = 16;
    }
```

whitebox

```
linbits_x2 = x2 - 15u;
ext <<= linbits;
ext |= linbits_x2;
xbits += linbits;
x2 = 15u;
```




```
linbits_x2 = x2 - 15u;
ext <<= linbits;
ext |= linbits_x2;
xbits += linbits;
x2 = 15u;
```

Summary

- Computation with encrypted data & function
  - strong whitebox attacker model
- Whitebox cryptography tries to be better than classical obfuscation alone
  - mathematical-level proofs for cryptographic primitives
- Implementation of selected schemes (almost ☺) released
  - published attacks as well

Questions 

Thank you for your attention!

Questions